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Romain Marteau, Vincent Moron, Nathalie Philippon. Spatial coherence of monsoon onset over Western and Central Sahel (1950-2000). *Journal of Climate*, 2009, 22 (5), pp.1313-1324. 10.1175/2008JCLI2383.1 . hal-00321044

**HAL Id: hal-00321044**

**<https://hal.science/hal-00321044>**

Submitted on 15 Jan 2010

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NOTES AND CORRESPONDENCE

**Spatial coherence of monsoon onset over Western and Central Sahel (1950-2000)**

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*Journal of Climate, submitted.*

December, 10 2007

*Revised version*

July, 07 2008

*Second revision*

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## 28Abstract:

29The spatial coherence of boreal monsoon onset over Western and Central Sahel (Senegal, Mali,  
30Burkina-Faso) is studied through the analysis of daily rainfall data for 103 stations from 1950 to  
312000. Onset date is defined using a local agronomic definition, i.e. the first wet day ( $> 1$  mm) of  
321 or 2 consecutive days receiving at least 20 mm without a 7-day dry spell receiving less than 5  
33mm in the following 20 days. Changing either the length and/or the amplitude of the initial wet  
34spell, or the length of the following dry spell modify the long-term mean local-scale onset date  
35but has only a weak impact either on its interannual variability or its spatial coherence. Onset  
36date exhibits a seasonal progression from southern Burkina-Faso (mid May) to northwestern  
37Senegal and Saharian edges (early August). Interannual variability of the local-scale onset date  
38does not seem to be strongly spatially coherent. The amount of common or covariant signal  
39across the stations is far weaker than the inter-station noise at the interannual time scale. In  
40particular, a systematic spatially-consistent, advance or delay of the onset is hardly observed  
41across the whole Western and Central Sahel. In consequence, the seasonal predictability of  
42local-scale onset over the Western and Central Sahel associated for example with large-scale  
43sea surface temperatures, is, at best, weak.

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### 531. Introduction

54The rainy season over the Sahelian belt spans only few months, mainly from July to September  
55(Lamb 1978; Nicholson 1979, 1980), and is associated with the latitudinal shift of the whole  
56monsoon system. Previous work has shown that the northward shift, which determines the  
57large-scale onset of the rainy season across the Sudanian and Sahelian belts, usually occurs at  
58the end of June, as an abrupt jump between Guinean (i.e. 5°-8°N) to Sahelian (i.e. 10°-14°N)  
59latitudes (Sultan and Janicot 2000, 2003; Sultan et al. 2003; Fontaine and Louvet 2006). The  
60monsoon withdrawal in late September over the Sahelian belt is much smoother (Sultan and  
61Janicot 2000). "Pre-onset" scattered rains could occur over the Sahelian belt before the large-  
62scale S-N jump, while most of the Sahelian seasonal rainfall are associated with westward-  
63moving squall-lines (SLs) of mean horizontal extent of ~ 500 km and propagation speed of 10-

6415 m/s (i.e. Martin and Schreiner 1981; D'Amato and Lebel 1998; Laurent et al. 1998; Mathon  
65et al. 2002).

66

67The timing of the start of the rainy season is crucial to decide when to plant crops (Sivakumar  
681992). This is of particular importance for the Sahelian belt where economy is mostly based on  
69rainfed agriculture, with weak capacity to mitigate adverse effects of interannual variability of  
70rainfall (Ingram et al. 2002). In that context, any reliable prediction of the local-scale onset date  
71would be of a great value to assist on time preparation of farmlands, mobilisation of seed,  
72manpower and equipment, and would also reduce the risks of planting at an unfavorable time  
73(Omosho et al. 2000). Sultan et al. (2005) clearly demonstrated that the "ideal" sowing date,  
74i.e. the one leading to the highest yields, is close to the large-scale onset date, defined as the  
75northward jump of the Intertropical Convergence Zone (ITCZ).

76

77The definition of the onset of the rainy season over West Africa has generally followed two  
78approaches: (i) a local-scale one and (ii) a large-scale one. Methods for detecting the onset of  
79the rainy season at local-scale have been proposed as early as the 70's for specific Sahelian  
80settings (in Niger mainly, Davey et al. 1976; Benoit 1977). Most methods rely on *in-situ* daily  
81measurements of rainfall meeting subjective thresholds (Davey et al. 1976; Stern et al. 1981;  
82Sivakumar 1988; Jolliffe and Sarria-Dodd 1994; Balme et al. 2005). These empirical thresholds  
83are chosen according to the climatological properties of the rainy season as well as agronomic  
84criteria (these points will be detailed in section 3). In this approach, the onset is primarily

85assumed as a change in the properties, frequency and/or intensity of rainfall events associated  
86with the arrival of the monsoon air mass. Other parameters have also been taken into  
87consideration to detect local onsets, such as evapotranspiration (Benoit 1977; Ati et al. 2002).

88

89A more recent large-scale approach is based on sub-continental indexes of observed rainfall or  
90rainfall proxies such as outgoing long wave radiation (OLR) (Sultan and Janicot 2000). The  
91seasonal cycles of pentad rainfall averaged over West African longitudes (e.g. 10°W-10°E)  
92show an alternation of steep increases and pauses (Louvet et al. 2003) during its northward  
93progression. One of these pulses appears to be associated with the abrupt northward shift of the  
94ITCZ, the so-called "ITCZ jump" (Sultan and Janicot 2000). The onset is thus only defined  
95from the planetary-scale northward shift of the monsoon, and a single date is given for a given  
96band of longitudes.

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98The approach of Camberlin and Diop (2003) can be viewed as an intermediate approach. In  
99their study, an Empirical Orthogonal Function (EOF) analysis is applied to local-scale, daily  
100rainfall anomalies in Senegal for a multi-year period. A single onset date was then computed  
101for the whole country as the minimum of the cumulative sum of the leading principal  
102component (PC) time series on a yearly basis. This date is representative of the local-scale onset  
103dates for the stations highly correlated with the leading PC, and part of local-scale interstation  
104noise is filtered out through the spatial weighting provided by the EOF.

105

106This brief review demonstrates that at least two different strategies are used to define the onset.  
107The local-scale definition is clearly the most suitable for end-users so that they can use the  
108information as a valuable decision-making parameter. In that context, three important related  
109questions are explored in this paper:

- 110       1. How pertinent is the local-scale definition, proposed in previous studies for specific  
111       settings across the Sahel, for a larger longitudinal belt? The previous definitions are  
112       based on subjective thresholds chosen according to climatological and/or agronomic  
113       features. The sensitivity of the onset date (in terms of mean and interannual variability)  
114       to this parametrization has never been evaluated.
- 115       2. To what extent do the average and local-scale onset date match with the regional-  
116       scale (i.e. as defined by Sultan and Janicot, 2000) ones? Is the abrupt jump of the ITCZ  
117       noticeable across the network? These issues are related to the shape and intensity of  
118       potential modes of variability of onset date. They are also intrinsically related to the  
119       intensity of the spatial coherence and potential predictability of onset date.
- 120       3. The spatial coherence of a phenomenon is partly indicative of its potential  
121       predictability: It is indeed expected that global or regional-scale sea surface  
122       temperatures anomalies should induce a rather smooth, roughly spatially-uniform,  
123       anomalous signal at regional-scale, at least for a flat area such as the Sahel (Moron et al.  
124       2006, 2007). As forecasts of the rainy season onset is desired by user communities, an  
125       estimate of its potential predictability is a first step toward this goal.

126

127 These three issues are analyzed from a 103 rain-gauge network covering Western and Central  
128 Sahel (Senegal, Mali and Burkina-Faso) from 1950 to 2000. Section 2 describes the different  
129 daily rainfall datasets. Section 3 provides the main results in terms of (i) definition of the local-  
130 scale onset date, (ii) climatological mean and characteristics of the rainfall field before and after  
131 the onset, (iii) interannual variability and spatial coherence of onset date. Conclusions are given  
132 in section 4.

133

## 134 2. Daily rainfall data

135 The daily rainfall analysed in this study come from two different databases: (i) the FRIEND-  
136 AOC (Flow Regimes from International Experimental and Network Data - Afrique de l'Ouest et  
137 Centrale) group (<http://armspark.msem.univ-montp2.fr/FRIENDAOC/>), and (ii) the Senegalese  
138 DMN (Direction de la Météorologie Nationale) that provided us with *in situ* daily data of 103  
139 stations for the period 1950 to 2000 (Fig. 1).

140

### 141 a. Rainfall data

142 Data for 33 stations in Mali and 41 stations in Burkina-Faso were compiled by the FRIEND-  
143 AOC group from various sources (IRD – Institut de Recherche pour le Développement –,  
144 ASECNA – Agence pour la SECurité de la Navigation Aérienne en Afrique –, DMN –  
145 Direction Météorologique Nationale – and CIEH – Comité Inter-Africain d'Etudes  
146 Hydrauliques –).

147



148Daily rainfall amounts recorded at 29 stations come from the Senegal DMN. Most of the  
149stations are located in the western part of the country while the eastern part is less sampled (Fig.  
1501).

151

#### 152*b. Filling the missing values*

153Missing daily rainfall observations (less than 3%) were replaced with a local scaling (Widmann  
154et al. 2003; Ines and Hansen 2005; Schmidli et al. 2006) of daily ERA-40 rainfall. For each  
155station, the closest ERA-40 grid point is chosen, and its daily rainfall is scaled so that the  
156frequency of occurrence of wet day  $> 1$  mm and the mean intensity of daily rainfall during wet  
157days match the long-term monthly mean of the available data. Missing entries are then replaced  
158by the calibrated ERA-40 rainfall for these particular days. Note that replacing the missing  
159entries from May to October with a simple stochastic weather generator ([Wilks 1999](#)) leads to  
160very similar results.

161

### 162**3. Results**

#### 163*a. Agronomic definition of onset*

164The local-scale agronomic definition of the onset is the most relevant to agriculture  
165management. This definition is based on local-scale daily rainfall using empirical thresholds of  
166rainfall that ensure enough soil moisture during planting and growing periods to avoid crop  
167failure (Walter 1967; Omotosho 1990 1992; Omotosho et al. 2000). Table 1 lists the different  
168thresholds used in selected previous studies dedicated to the Sahelian domain. Most of the

169 studies agree on two criteria; (i) 1 or 2 consecutive days receiving at least 20-25 mm of rainfall,  
170 and (ii) no 7-day dry spell in the following 30 days from the onset. The threshold of 20 mm  
171 amount was adopted following a study by ICRISAT dedicated to millet in Niger (Davey et al.  
172 1976; Sivakumar 1992) and corresponds to the minimum water requirement for crop survival.  
173 Considering at least 2 consecutive days is a reasonable choice to take into account a rain event  
174 that occurs across the recording time (usually between 7 and 9 a.m local time). In fact, SLs  
175 develop themselves mainly in late afternoon and persist sometimes during the night (Martin and  
176 Schreiner 1981). The 7-day dry spell after the onset is known as the "control period" and  
177 prevents against "false" onsets that have disastrous consequences on germination and crop  
178 development (Sivakumar 1992), and require farmers to sow again while the seed's stock is  
179 usually small (Diop 1996). Moreover, anything less than 50 percent of the weekly crop water  
180 requirement (CWR) will likely lead to crop failure (i.e. Omotosho et al. 2000). The CWR  
181 equals at least 10 mm across the Sahel, leading to a threshold of 5 mm in 7 days to define a  
182 dangerous limit for crop survival after the first rains.

183

184 In the current study, a wet (dry) day is defined as a day receiving more (less) than 1 mm (Diop  
185 1999) because (i) rainfall amounts between 0 and 1 mm are not equally reported across  
186 countries and stations (i.e. synoptic or not), and (ii) considering daily amounts less than 1 mm  
187 usually increases the interstation noise (Moron et al. 2007) when determining onset. The onset  
188 date (OD hereafter) is defined here as the first wet day of 1 or 2 consecutive days receiving at  
189 least 20 mm without any 7-day dry spell receiving less than 5 mm during the following 20 days

190counted from the onset. OD is computed from May, 1<sup>st</sup>. These criteria are obviously too  
191restrictive for the driest stations and years. While less than 0.4% of station-year do not  
192experience any 2-day receiving at least 20 mm during May-November season, 8.6% of onset  
193are undefined when the post-onset 7-day dry spell receiving less than 5 mm in the following 20  
194days is included in the definition. This percentage reaches 19% when the control period length  
195is extended to 30 days from the initial wet spell. A window of 20-day is thus retained as a  
196compromise between the need to consider "false" starts and a too restrictive threshold that  
197excludes many stations and years. Undefined onset dates still account for 40% of years for the  
19814 stations north of 15°N. In most of these cases, no rainy season is actually experienced with  
199scattered rainy events spread across the season. In the following analyses (except for EOF in  
200section 3d), the undefined onset dates (8.6%) are replaced by the latest available onset date  
201observed across the network for the given year, weakly increasing the spatial coherence over  
202the northern edge of the domain.

203

204Figure 2a displays the mean onset dates averaged over the 51 years. The mean OD exhibits a  
205rather regular northward shift , mixed with a secondary northwestward one over Senegal, from  
206mid May (south Burkina Faso) to early August (NW Senegal and central-northern Mali).  
207Respectively, 17.9%, 31.4%, 36.1% and 12.7% of onset occur in May, June, July and August  
208(Fig. 2b).

209

210*b. Mean characteristics of rainfall field before and after the onset*

Figure 3 shows the mean characteristics of the rainfall field averaged over the 15 days before and 15 days after the local-scale OD. These periods are extracted for each station on a yearly basis, and the frequencies of occurrence of wet days receiving respectively between 1 and 20 mm and  $> 20$  mm are computed (Fig. 3a-d) as well as the mean length of the wet and dry spells (Fig. 3e-h).

216

Before the onset, the frequency of occurrence of wet days receiving between 1 and 20 mm is far from zero (usually 10-20%). By contrast, the frequency of occurrence of wet days receiving  $> 20$  mm is very low (1-4%), but this is almost fully explained by the criteria used to define OD (see section 3a). The mean dry spell length is rather homogeneous, usually between 4 and 6 days, without any clear northward increase (Fig. 3g). Similarly, the mean wet-spell length is rather spatially uniform, between 1 and 2 days, still without any clear northward decrease (Fig. 3e).

224

From the onset, the frequency of occurrence of wet day receiving between 1 and 20 mm increases smoothly, by a factor of 2, while the frequency of occurrence of wet day  $> 20$  mm is roughly multiplied by 5. The multiplication of wet days breaks up the dry spells, that are consistently shorter than before the onset (less than 3 days except for several northern stations, Fig. 3g,h) while the mean wet spell length remains shorter than 2 days (Fig. 3i,j). In other terms, at local-scale, the onset is usually associated with more and wetter rainy days afterwards, but those wet days remain rather isolated or clustered into 2-day wet sequences. This could be

related to the dominant influence of SLs and the usual scarcity of long-lasting wet spells at these latitudes.

234

Figure 4 further illustrates the relative rainfall field near the onset date, in particular its spatial pattern. For each station and each year, the frequency of occurrence of daily rainfall  $> 1$  mm for 2 days before (Fig. 4a), and after (Fig. 4b) the local-scale onset (and their difference, Fig. 4c) is computed for the whole rainfall field relocated relative to the reference station (i.e. (0,0) location on Fig. 4). In other words, Figures 4b,c illustrate the spatial coherence of the "first kind", i.e. the frequency of occurrence of a wet day around a station when its onset occurs. Figure 4a is roughly similar to the mean climatological pattern of frequency of occurrence, i.e. a northward gradient, also visible in the mean onset date (Fig. 2). Considering the long-term mean of the frequency of occurrence of any other sample of 2 days leads roughly to the same pattern, except that the spatial mean varies according to the seasonal cycle of rainfall (not shown). The occurrence of local-scale OD slightly alters this pattern (Fig. 4b), mostly through an increase of the frequency of occurrence of an elongated WSW-ENE shape around the reference station (Fig. 4c). A small asymmetric surface of  $3^{\circ}$ - $4^{\circ}$  ( $\sim 1^{\circ}$ ) in longitude by  $2^{\circ}$  ( $\sim 1^{\circ}$ ) in latitude around the reference station exhibits significant (at the two-sided 90% level according to a Student's T test) increase of the frequency of occurrence for 75% (90%) of the time between pre- and post-onset 2 days (Fig. 4c). Thus, figure 4 suggests that local-scale OD seems hardly related to coherent space-time propagating features at meso- or synoptic-scale and/or even the planetary-scale because neither regular northward (possibly associated with an

253 abrupt jump of the ITCZ), nor westward (possibly associated with a SL) progression appears  
 254 between panel (a) and (b) of Figure 4. Increasing the length of the time period averaged before  
 255 and after the onset to 5, 10, 20 and 30 days is associated with a wider ~ W-E belt of increased  
 256 frequency of occurrence of rainfall, probably in relation with the mean northward shift of the  
 257 overall rain belt, especially for periods lasting at least 10 days (not shown).

258

#### 259 *c. Spatial coherence of the onset date at interannual time scale*

260 The spatial coherence of the "second kind" is the possible systematic modulation of onset dates  
 261 (or any other seasonal characteristic) at interannual time scale. Note that a weak spatial  
 262 coherence of the "first kind" (section 3b) does not necessarily forbid this effect because a large-  
 263 scale forcing could synchronize the onset dates in time, by systematically delaying or bringing  
 264 forward the onset of the rainy season at local-scale (Moron et al. 2008). The spatial coherence  
 265 of the OD at interannual time scale has been estimated through degrees of freedom (DOF)  
 266 (Moron 1994; Fraedrich et al. 1995; Bretherton et al. 1999; Moron et al. 2006) and interannual  
 267 variance of the standardized anomaly index (SAI) ( $\text{var}[\text{SAI}]$ ) (Katz and Glantz 1986). The DOF  
 268 are computed following the equation of Fraedrich et al. (1995):

269

$$270 \quad DOF = \frac{M^2}{\sum_{i=1}^M e_i^2}$$

271

272 where  $M$  is the number of stations and  $e$ , the eigenvalues of the correlation matrix. The DOF  
 273 varies between 1 and the rank of the correlation matrix. In the limiting case of  $e_i = 1$  for all

274 orders,  $\text{DOF} = M$ , that is, each station conveys independent information and the common  
 275 "signal" is zero. On the other hand, if the first eigenvalue accounts for all variance of the field,  
 276 then  $\text{DOF} = 1$ , that is, each station conveys the same information equal to the signal and the  
 277 noise is zero. Note that due to finite length, the highest DOF expected for a  $51 \times 103$  matrix of  
 278 independent white noise is not 50, but rather  $\sim 34$ . The  $\text{var}[\text{SAI}]$  ranges between 0 (correlation  
 279 of -1 between two equal-sized and perfectly out-of-phase samples),  $1/M$  ( $\sim 0.01$  in our case, for  
 280 spatially independent variations), and 1 (perfect correlation between stations) (Moron et al.  
 281 2006, 2007).

282

283 Here the DOF of the local-scale OD is high (23.7) indicating a weak spatial coherence at the  
 284 regional scale. The  $\text{var}[\text{SAI}]$  equals 0.07 and is also close to the value associated with a white  
 285 noise time series. For comparison, the DOF and  $\text{var}[\text{SAI}]$  equal 6.1 (respectively 4.8) and 0.36  
 286 (respectively 0.41) for the May-November seasonal rainfall amounts (respectively frequency of  
 287 occurrence of wet days  $> 1$  mm). Therefore, according to DOF and  $\text{var}[\text{SAI}]$ , the agronomic  
 288 OD is characterized by a considerable amount of inter-station noise, and in consequence, is  
 289 assumed to be poorly predictable from large-scale predictors at the interannual time scale  
 290 (Moron et al. 2006, 2007). To test the sensitivity of the spatial coherence to parametrization,  
 291 DOF and  $\text{var}[\text{SAI}]$  have been computed again, by changing (i) the length of initial wet spell ( $L_w$   
 292 = 2 to 10 days) and (ii) the amount of rainfall received during the initial wet spell ( $A_w = 1, 5,$   
 293 10, 15, 20, 25, 30, 35 and 40 mm) while the other criterion (i.e. a 7-day dry spell receiving less  
 294 than 5 mm in the following 20 days) is kept fixed. Note that the percentage of undefined onset

295 dates is always  $< 10\%$  ~~in mean~~, except when  $A_w > 25$  mm and  $L_w < 4$  days (maximum of  
296 undefined onset = 19.1% for  $A_w = 40$  and  $L_w = 2$ ). As before, the missing entries are replaced  
297 by the latest interannual onset date, slightly increasing the spatial coherence on the northern  
298 edges.

299

300 DOF and  $\text{var}[\text{SAI}]$  are indeed very stable amongst the 81 different estimates; DOF varies  
301 between  $\sim 23$  and  $\sim 28$  with 88% of values between 23 and 25 and  $\text{var}[\text{SAI}]$  varies between  
302 0.065 and 0.086. In other words, increasing the length and/or amplitude of the initial wet spell  
303 has a very weak impact on the spatial coherence. Even the climatological long-term mean and  
304 the interannual variability at local-scale are only weakly sensitive to the parametrization of  $A_w$   
305 and  $L_w$ . 52% (respectively 76%) of the local-scale mean bias between two different estimates of  
306 OD are less than 5 days (respectively 10 days) in absolute value and 77% (respectively 88%) of  
307 the local-scale correlations between two different estimates of OD are equal or greater than 0.7  
308 (respectively 0.6). The impact of the length of the control dry spell ( $L_d$ ) was also tested with  $A_w$   
309 and  $L_w$  set to 20 mm and 2 days respectively, while  $L_d$  was set equal to 5, 7, 9, 11, 13, and 15  
310 days in the 20 days from the onset. Note that undefined onsets decrease almost exponentially  
311 from 25% to 1% between the extreme values of  $L_d$ . DOF and  $\text{var}[\text{SAI}]$  are almost stable  
312 between 25 and 26 and  $< 0.10$  respectively. In summary, the weak spatial coherence of "second  
313 kind" is not related to the parametrization of the OD.

314

315



316

317*d. Interannual to interdecadal variability of the onset date*

318To further examine the interannual variability of OD, an Empirical Orthogonal Function (EOF)  
319analysis based on its correlation matrix is computed. Note that undefined onsets are left  
320untouched here and that correlation matrix is computed only from pairs of available ODs. The  
321leading EOF mode of OD accounts for 8.7% of the total variance consistently with the weak  
322spatial coherence depicted above. By contrast, the leading EOF of the May-September seasonal  
323amount (the frequency of occurrence of wet days > 1 mm) accounts for 38.1% (respectively  
32443.4%) of the total variance. The second unrotated EOF mode of onset date explains less than  
3256.4% of total variance. The first unrotated mode (Fig. 5a) describes a relatively coherent  
326structure of OD variability mostly over Western and Central Senegal. This behaviour could be  
327at least partly related to the relatively high spatial sampling (Fig. 1), but could be also related to  
328a slightly stronger signal (Camberlin and Diop 2003). The corresponding leading EOFs of  
329seasonal amount (Fig. 5b) and frequency of occurrence of wet days > 1 mm (Fig. 5c) exhibit  
330larger scale patterns with loadings > 0.6 spread all across the domain without a clear spatial  
331gradient. The leading PC of onset date (respectively seasonal amount and frequency of  
332occurrence) (Fig. 5d) exhibits a positive (negative) and statistically significant (at one-sided  
33395% confidence level) trend, i.e. a delayed onset (decreased seasonal rainfall and frequency of  
334occurrence) from 1950-2000. The median of local-scale correlations between onset on one hand  
335and seasonal amount and frequency of occurrence on the other hand equals only -0.35.

336

337 In order to analyse the relationships between the local-scale and the regional-scale onset date as  
 338 defined by Sultan and Janicot (2000) through the S-N jump of the ITCZ the local-scale OD are  
 339 extracted from 1968 (available online at <http://www.lodyc.jussieu.fr/~bslod/monsoon.htm>).  
 340 Note that DOF of local-scale OD for the 1968-2000 period equals ~19, but this apparent higher  
 341 spatial coherence could be an artefact of the decrease of the matrix rank from 50 to 32. The  
 342 correlations between the large-scale and the 103 local-scale ODs are between -0.54 and 0.41,  
 343 with only 7 values being significant at the two-sided 95% level according to a random phase  
 344 test (Janicot et al. 1996). Moreover, the correlation between regional-scale OD as defined by  
 345 Sultan and Janicot (2000) and a regional index (SAI) or the leading PC of onset date equals  
 346 only 0.06 and 0.24 (both values are not significant at the two-sided 90% level). The large-scale  
 347 onset is divided in 3 terciles of early (1969, 1982, 1985, 1973, 1978, 1994, 1996, 1999, 1993,  
 348 1974, 1977), near-normal (1990, 1992, 1975, 1980, 1970, 1983, 1986, 1968, 1976, 1971, 1979)  
 349 and late (1981, 1972, 2000, 1985, 1988, 1997, 1984, 1989, 1987, 1998, 1991) jumps of the  
 350 ITCZ. The local-scale OD anomalies are then averaged for the three sets of years. There is a  
 351 considerable amount of inter-station noise for each of the terciles and the number of stations  
 352 where the OD anomaly is significantly different from zero (based on a one-sided t-test at the  
 353 90% confidence level) is always less than 15% (not shown).

354

355 Lastly, the teleconnections between local scale OD and four sea surface temperature (SST)  
 356 indices, capturing ocean sectors known for exerting an influence over West African Monsoon  
 357 were considered (i.e. Nicholson 1986; Ropelewski and Halpert 1987; Rowell et al. 1995;

358 Nicholson and Kim 1997; Janicot et al. 1996, 2001). These indices include the east equatorial  
 359 Pacific (NINO3.4, 170°W-120°W; 5°S-5°N), the North Tropical Atlantic (NATL: 60°W-30°W;  
 360 5°N-20°N), the South Tropical Atlantic (SATL: 30°W-10°E; 0°-20°S) and the Guinean Gulf  
 361 (GGUI: 10°W-10°E; 5°S-5°N). Figure 6 displays distribution of correlation coefficients  
 362 between local-scale OD and each SST indices averaged over May-July (i.e. including ~85% of  
 363 the local-scale onset, Fig. 1) for 1950-2000, 1950-1969 and 1970-2000. At least 50% of  
 364 correlation coefficients are between -0.2 and +0.2 and the significant value are usually scattered  
 365 in space (not shown). In summary, the teleconnections between the SST related to the ENSO  
 366 phenomenon, the Tropical Atlantic dipole, or Guinea Gulf and local-scale OD seem weak.

367

#### 368 4. Conclusion

369 The main goal of this paper was to analyze the spatial coherence, robustness and the interannual  
 370 variability of the local-scale onset date (OD) of the boreal summer monsoon over Western and  
 371 Central Sahel (Mali, Burkina-Faso, Senegal) from a network of 103 rain gauges (Fig. 1) with  
 372 almost complete records from 1950 to 2000. The local-scale OD is first defined as the first wet  
 373 day  $\geq 1$  mm of one or two consecutive day receiving at least 20 mm without any 7-day dry spell  
 374 receiving less than 5 mm in the following 20 days from the onset. This local-scale definition  
 375 follows previous studies (Stern et al. 1981; Sivakumar 1988; Omotosho 1990; Jolliffe and  
 376 Sarria-Dodd 1994; Omotosho et al. 2000; Dodd and Jolliffe 2001) and is best suited for end-  
 377 user purposes since it explicitly takes into account the rainfall demand for crop seeding and  
 378 survival during the first stages of growth. This analysis complements previous similar studies

379(summarized in Table 1) which typically considered a smaller subset of stations and did not  
380deeply investigate the sensitivity of the mean OD and its variability related to the subjective  
381parameters used in its definition such as the length and amplitude of the initial wet spell.

382

383The spatial coherence of OD is analyzed from two points of view: (i) a quasi-instantaneous  
384pattern of rainfall when onset date occurs at a particular station (Fig. 4) and (ii) the  
385synchronization of onset dates at interannual time scale, i.e. the possible systematic modulation  
386of onset dates across the Sahelian band (Fig. 5). The spatial coherence of the "first kind"  
387exhibits a small, significant increase of frequency of occurrence of rainfall relative to pre-onset  
3882-day (Fig. 4c). This could be associated with a range of factors, from convective cells to meso-  
389convective clusters that probably trigger the local-scale onset. The spatial coherence of the  
390"second kind" is analyzed through empirical estimates of the degrees of freedom (DOF) or  
391interannual variance of the Standardized Anomaly Index ( $\text{var}[\text{SAI}]$ ). Both estimates suggest a  
392weak spatial coherence, i.e. the onset date is hardly systematically synchronized at interannual  
393time scales. This is also demonstrated by the weak amount of variance accounted for by the  
394leading EOF (Fig. 5a). These results contrast with the seasonal amount and the frequency of  
395occurrence which exhibit a large-scale pattern across the whole belt analyzed (Fig. 5b,c). The  
396weak spatial coherence of the "second kind" is almost independent of the parametrizations used  
397in the definition of the onset date.

398

399These suggest that large-scale potential forcing seems unable to systematically synchronize the  
400occurrence of the first rains above a fixed threshold across the western and central Sahel. The  
401occurrence of the local-scale onset could be hardly viewed as a systematic event across year  
402and station, but merely a complex product of the multi-scale phenomena that produce rainfall  
403over this area. The discrepancy between the local-scale OD defined here and the regional-scale  
404onset defined by the northward jump of the monsoon is especially puzzling and needs further  
405investigation. It is possible that local-scale onset as defined here could be associated either with  
406a localized convective event, even before the S-N jump of the ITCZ, or with a meso-scale  
407squall line. But even in this latter case, the timing of occurrence, size, location and track of the  
408first squall line of the rainy season are hardly reproducible from one year to the next. In other  
409words, there are too many different phenomena, or different scales of motion, that could lead to  
4105-40 mm rainy event in 2-10 days at local-scale. If the northward jump of the monsoon  
411enhances the probability of such events across the Sahel, the fact that ITCZ has moved to its  
412northernmost seasonal location, does not necessarily induce local-scale onset everywhere at the  
413same moment or even on a short time step.

414

415An important consequence is that local-scale OD appears to show little potential predictability  
416based on large and regional-scale boundary conditions such as sea surface temperatures and/or  
417soil moisture (Folland et al. 1986; Philippon and Fontaine 2002; Douville et al. 2007). This is  
418because the regional-scale seasonal potential predictability implies that the variable of interest  
419shares a variable, but significant, amount of common or covariant information at this scale, at

least for a flat area as Sahel. The fact that seasonal rainfall amount and frequency of occurrence are far more spatially-coherent than the onset date (i.e. DOF equals respectively 6.1, 4.8, and 23-28) suggests that most of the seasonal predictability of rainfall over the Sahelian belt is actually not associated with a systematic delay or advance of the local-scale onset as defined here, but stands out for example as a seasonally-varying or constant systematic modulation of the frequency of occurrence of rainfall across the season (Moron et al. 2007). This is not a trivial result, because local-scale onset sometimes conveys a spatially-consistent signal and potential predictability, as in Indonesia (Moron et al. 2008). This analysis emphasizes also the need to carefully examine the context of any local-scale analysis of the onset, because the weak spatial coherence implies a potential large uncertainty due to random sampling. More work is also needed to look at other definitions of the onset, for example integrating the daily rainfall in time and/or in space. The spatial noise is not necessarily evenly distributed across the scales and it would be interesting to look at intermediate scales between the local-scale and large-scale onsets. In particular, any definition that filters out some of the local-scale noise as the cumulative daily rainfall anomalies (Camberlin and Diop 2003; Liebmann et al. 2007) is especially appealing in this context. The apparent spatial increase of the signal over Western and Central Senegal (Fig. 5a) warrants also further studies.

437

**Acknowledgements:** We acknowledge the FRIEND-AOC group and Senegal DNM for providing us the rainfall data. R. Marteau is partly supported by the AMMA program. Based on a French initiative, AMMA was built by an international scientific group and is currently

441funded by a large number of agencies, especially from France, UK, US and Africa. It has been  
442the beneficiary of a large financial contribution from the European Community's sixth  
443Framework Research Program. Detailed information on scientific coordination and funding is  
444available on the AMMA International web site: <http://www.amma-international.org>. ECMWF  
445ERA-40 data used in this study have been freely obtained from the ECMWF Data Server  
446(<http://www.ecmwf.int>). We thank Gil Mahé and Benjamin Sultan for fruitful discussions.  
447Lastly, we thank two anonymous reviewers and the editor of this paper (D. Straus) for their  
448constructive comments which help us on clarifying the goals and results of our paper, and lastly  
449Bradfield Lyon (IRI, Columbia University) for his careful reading of the revised version of this  
450paper

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570

## 571 **Figures captions**

572 **Figure 1:** Location of the 103 Sahelian rain-gauge used in this study.

573 **Figure 2:** (a) Climatological (1950-2000) local-scale onset date (b) distribution of cumulative  
574 frequency of the local onset date (25, 50 and 75 percentiles are indicated by vertical dashed  
575 line)

576 **Figure 3:** Rainfall field statistics averaged over the 15 days before (left column) and from  
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584 the two-sided 90% level according to a Student's T test.

585 **Figure 5:** (a) Leading unrotated empirical orthogonal function (EOF) modes of the local-scale  
586 onset date, expressed as loadings, i.e. correlation between the corresponding Principal  
587 Component (PC) and the raw data. (b) Leading unrotated EOF of seasonal (MJJAS) amount of  
588 rainfall. (c) Leading unrotated EOF of seasonal (MJJAS) frequency of occurrence of rainfall  $>$   
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590 confidence level according to a Bravais-Pearson test. (d) leading principal component

591 timeseries of onset date (bars), seasonal amount (circle) and frequency of occurrence of rainfall  
592 (upper triangle).

593 **Figure 6:** Boxplot of correlation coefficients between local-scale onset date and NINO3.4,  
594 Tropical Atlantic dipole and Guinea gulf SST index for periods 1950-2000, 1950-1969 and  
595 1970-2000. Boxes are bounded by the first quartile, and third quartile of the distribution and the  
596 internal horizontal line is the median. Whiskers extend from the box out to the most extreme  
597 data value within 1.5 by the interquartile range. The boxes have lines at the lower quartile,  
598 median, and upper quartile values. The whiskers are lines extending from each end of the boxes  
599 to show the extent of the range of the data within 1.5 by the interquartile range from the upper  
600 and lower quartiles. The outliers are displayed by a cross. Outliers, displayed by a cross, are  
601 data with values beyond the ends of the whiskers. Italic values indicate the number of local-  
602 scale correlations significant at two-sided 95% confidence level according to a random phase  
603 test (Janicot et al. 1996).

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## 605**Tables captions**

606**Table 1.** Criteria of the agronomic definitions of the local-scale onset date of the rainy season  
607used in selected previous studies. All of these definitions start from daily rainfall observed at  
608rain-gauge stations.

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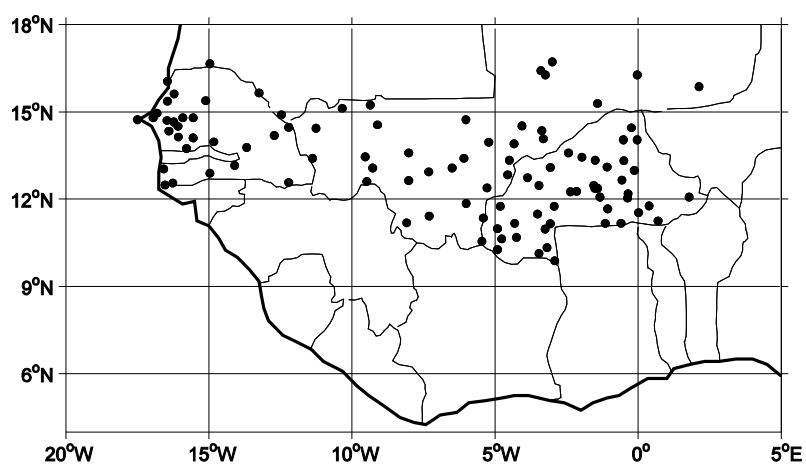
Authors	Data	Details of definitions	Study area	Number of stations	Study period
Stern et al. (1981)	Daily rainfall	- 2 successive days - receiving at least 20 mm	Transect S/N Benin, Nigeria, Niger, Mali	11 stations	1934-1965
Sivakumar (1988)	Daily rainfall	- 3 consecutive days - accumulating at least 20 mm - no dry period of 7 or more consecutive days in the following 30 days	Niger Burkina-Faso	58 stations	25 Years (not specified)
Omotosho (1990, 1992)	Daily rainfall	- first 4 falls receiving at least 10 mm - no dry spell of 7-day between any 2 such rains	Northern Nigeria & West Africa	3 stations	1973-1988
Dodd and Jolliffe (1994)	Daily rainfall	- 5 consecutive days (with at least two other wet days in the period) - accumulating at least 25 mm - no dry period of 7 or more consecutive days in the following 30 days	Burkina-Faso	22 stations	1902-1989

**Table 1.** Criteria of the agronomic definitions of the local-scale onset date of the rainy season used in selected previous studies. All of these definitions start from daily rainfall observed at rain-gauge stations.

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648 **FIGURES:**

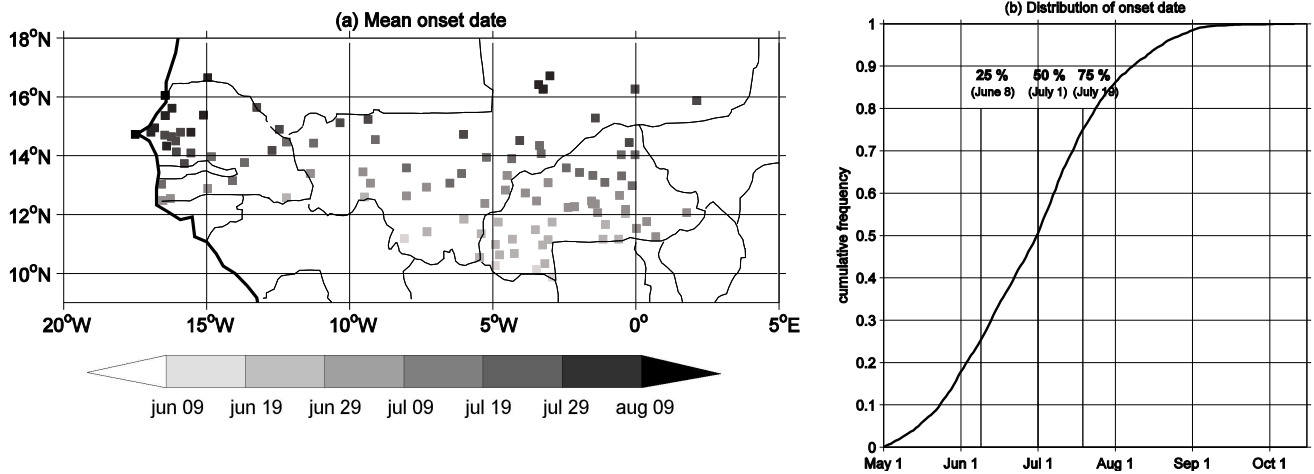
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651 **Figure 1.** Location of the 103 Sahelian rain-gauge stations used in this study.

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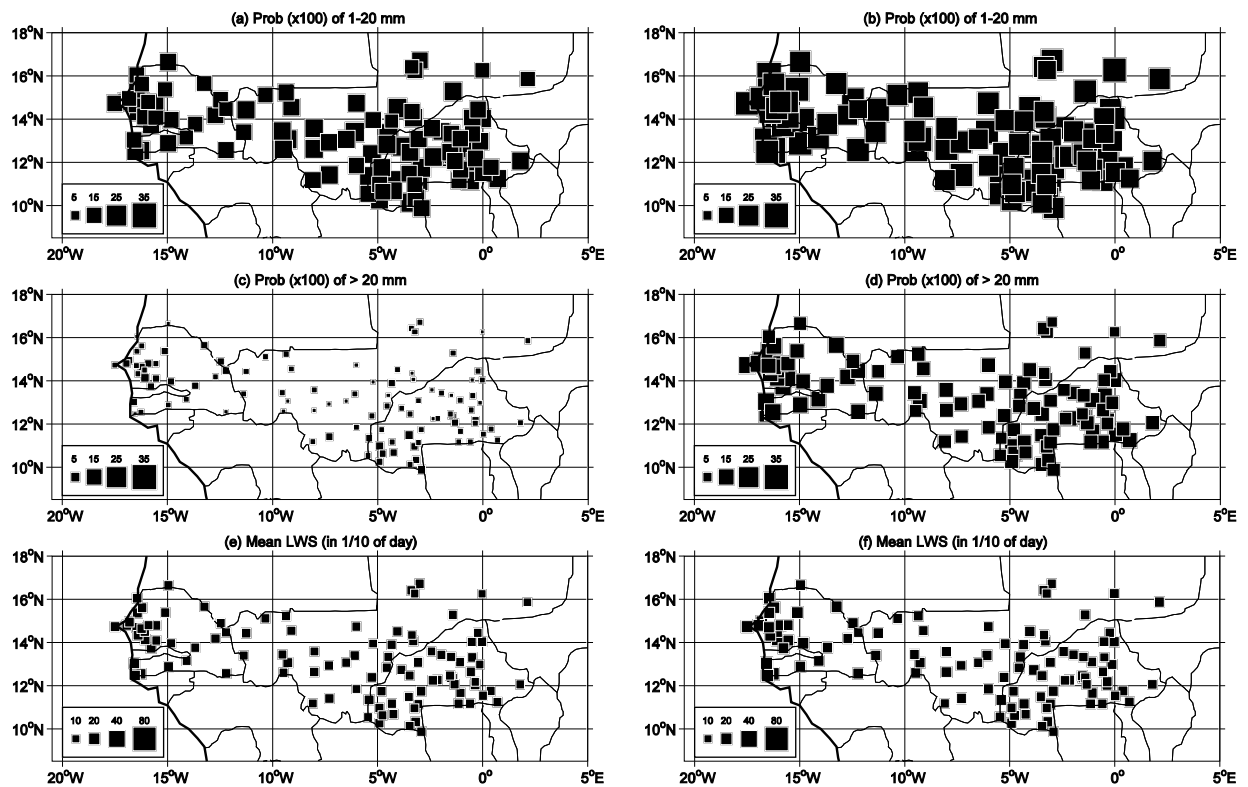


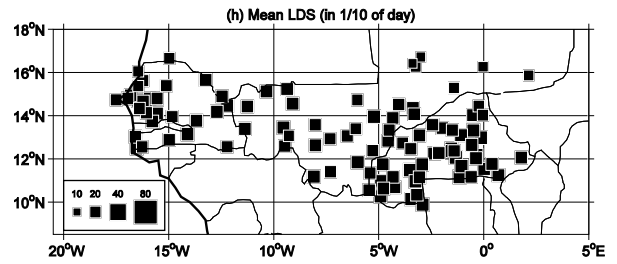
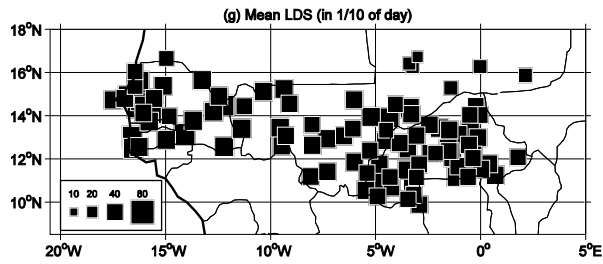
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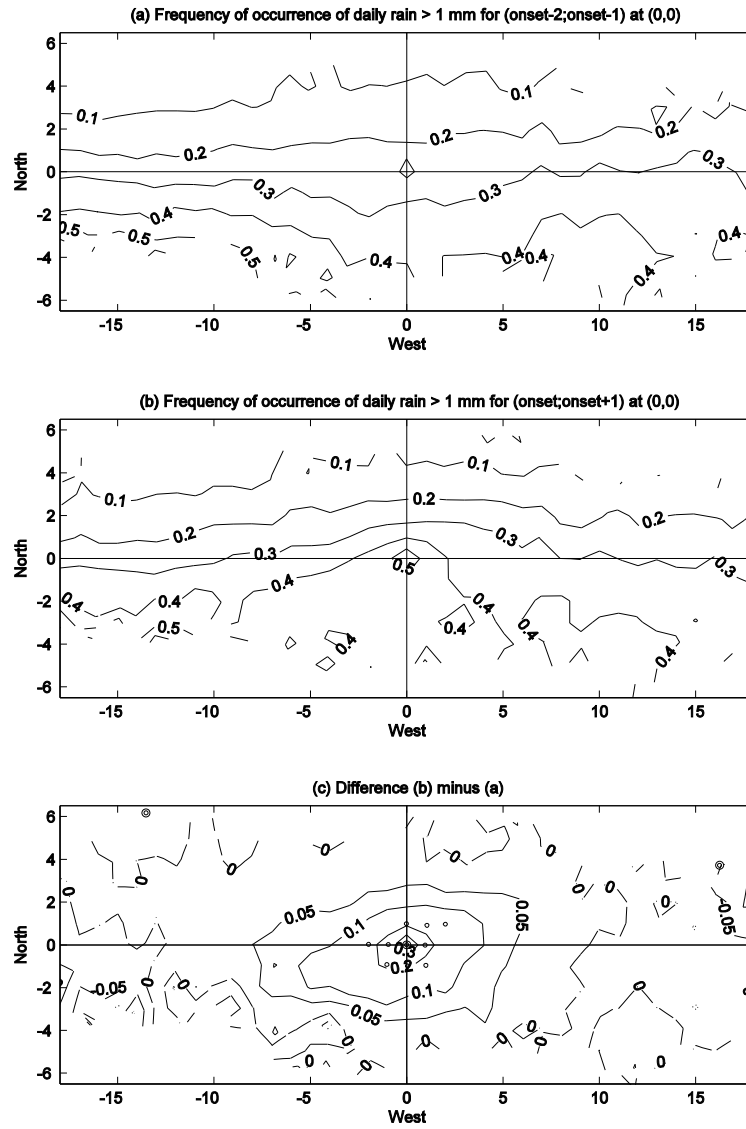
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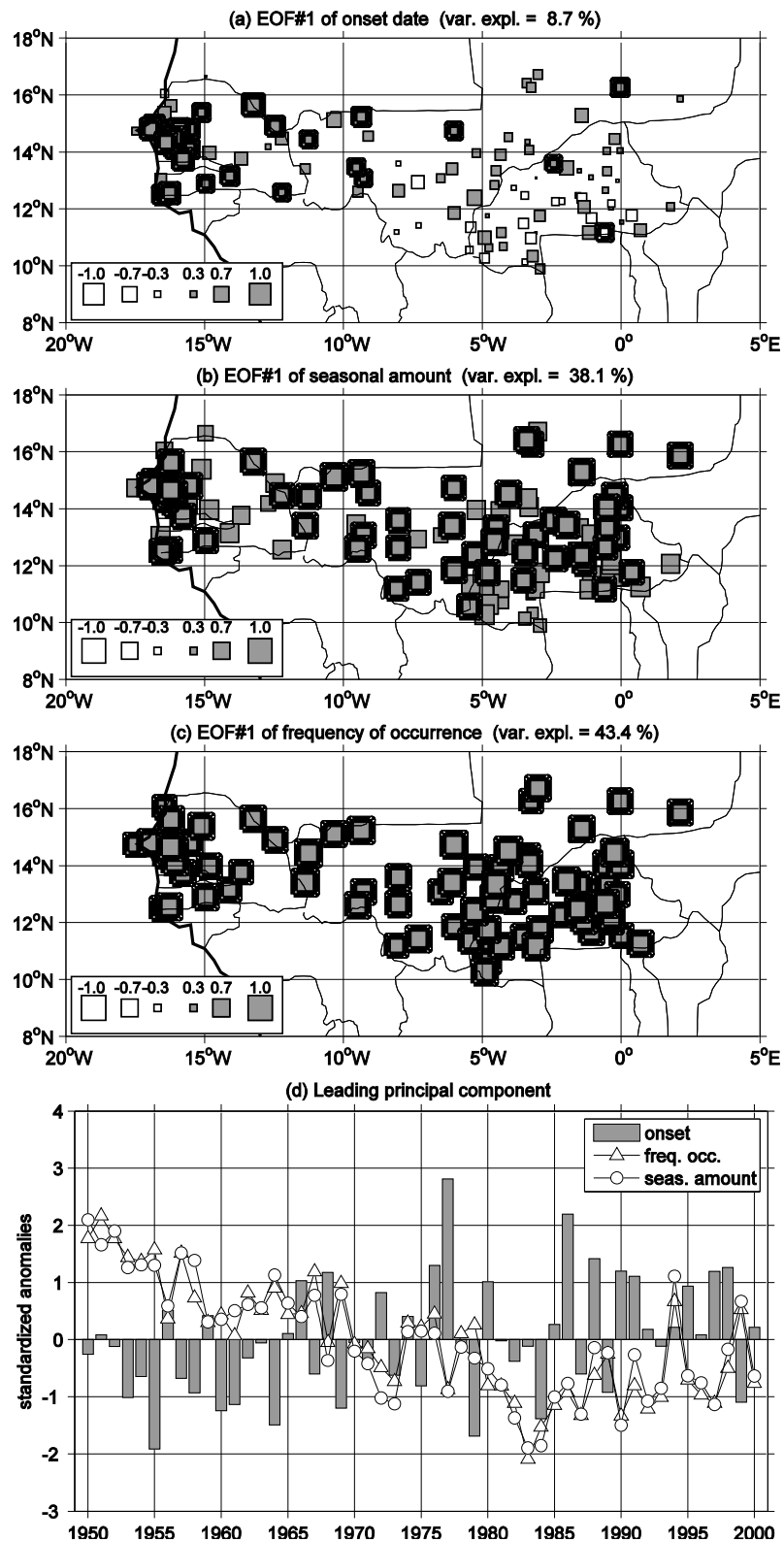
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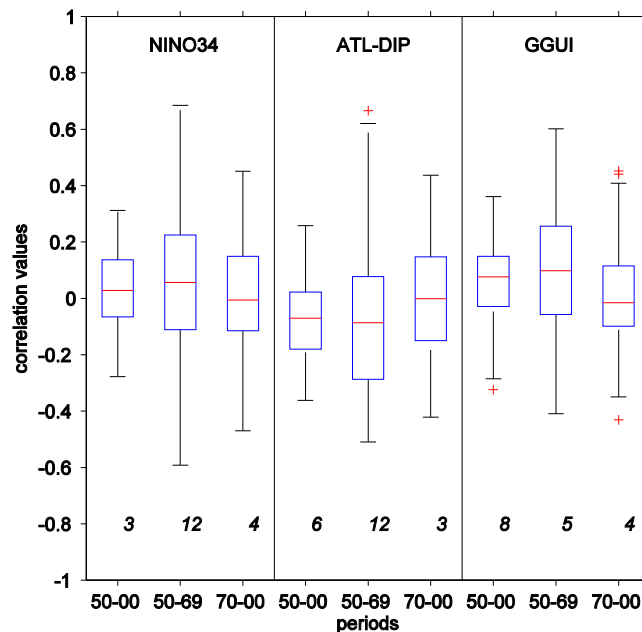
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